APPLICATION OF MODEL OUTPUT STATISTICS TO TROPICAL CYCLONE FORECASTING IN THE WESTERN PACIFIC

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Monterey, California

THESIS

Application of Model Output Statistics
to Tropical Cyclone Forecasting
in the Western Pacific

by

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by

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Lieutenant-United States Navy
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ABSTRACT

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I. INTRODUCTION

The development of analog techniques in forecasting is a logical extension to the experienced forecaster's recalling of past storms or synoptic situations. The latter should of course resemble the current situation in its essential characteristics. After some mental averaging the analog forecaster assumes that similar patterns will retain a certain degree of similarity through some period of further development. Generally, analog techniques select from climatological history a sample of analog storms which meet specific criteria with respect to the current storm, regarding date, geographical location, heading, and speed. Each analog storm is translated to the current position and started at the current storm's speed and heading. An average of the tracks which the analog storms subsequently followed is computed and used as guidance in forecasting the current storm's future track.

Analog forecasting techniques have been developed to forecast objectively the position of tropical cyclones in the Pacific by Jarrell and Somervell (1970) and in the Atlantic by Neumann and Hope (1970). The analog techniques have shown skill in forecasting tropical cyclones, and reflect to some degree most of the tracks future cyclones will take. The large climatological data base lends itself to statistically determined limits on the most likely tracks.

There are several areas of limitation in the analog techniques. First, they cannot forecast for storms which are far removed from the climatological mean for which there are

few if any analog storms. Second, they tend to forecast the least likely middle ground between the highly traveled westward track and the similarly frequented north or north-eastward recurvature path. Third, when separate means are used that include only recurving or straight analogs, such as is used in the analog program (TYFOON 73) at the Fleet Weather Central / Joint Typhoon Warning Center, Guam (FLEWEACEN / JTWC), the major problem of deciding between the two remains. Neumann and Hope (1972) found that the analog technique when applied to recurving storms had mean displacement errors approximately twice those of westward tracking storms. The analog technique inherently includes the interaction of the cyclone with its synoptic environment, which becomes more variable at the mid-latitudes of the recurving cyclone. However, the computed mean analog track only represents some average synoptic situation, and therefore the use of some current synoptic features, which can be related to storm displacement by statistically determined coefficients, should improve the accuracy.

The objective of this thesis was to investigate the relationships between current synoptic features and their influence on storm displacement. The technique of Model Output Statistics (MOS) given by the so called "ridge regression" type of biased estimator, vice the least squares estimator, were used to predict recurvature or non-recurvature of tropical cyclones in the Western Pacific. Corrections to an analog forecast position, given a recurvature or non-recurvature forecast, were also predicted.

II. DATA AND PREDICTORS

A. DATA

Historical data were obtained from the Fleet Weather Central / Joint Typhoon Warning Center, Guam, and the Fleet Numerical Weather Central (FNWC), monterey. The FLEWEACEN / JTWC data were for the tropical cyclones of 1974 and 1975 in the Western Pacific. The data were supplied at synoptic times 0000, 0600, 1200, and 1800 GMT, which represent effective times for FLEWEACEN / JTWC tropical cyclone warnings. At each of these warning times the JTWC initial position with the 24, 48, and 72 hour forecast positions from each of two versions of the TYFOON analog program were given. One technique was based on a history of "straight running" storms while the other was based on a history of "recurving" storms. The FNWC data were Northern Hemisphere 63 by 63 grid 500-mb height fields and surface pressure fields. Analysis fields as well as 24, 48, and 72-hour primitive equation prognostic fields were provided for the initial times 0000 and 1200 GMT.

The date time group of each JTWC storm warning was linked with the FNWC field times either 12 or 18 hours earlier since these were the latest field data operationally available at warning time. At each matching of data a forecast case was identified. For the years 1974 and 1975 data were available for a total of 564 24-hour forecast cases of which 356 persisted to 48 hours and 208 to 72 hours. These cases represented some portion of 44 tropical

cyclones.

Gross error checks were performed on the data, and errors recognized as clerical in nature were corrected where possible. Four cases with unreconcilable errors were eliminated. Approximately 80 percent of the cases (457) were used in the development of the forecasting technique, and 20 percent (125) were reserved as independent test cases. The independent sample was selected uniformly by using all the forecast cases from every sixth tropical cyclone.

B. PREDICTORS

For each forecast case (recall the matching of data) 234 possible predictors were calculated. (see Figure 1.) At each of the 14 points noted in figure 1., which were derived from the two proposed analog tracks, two gradients were measured on each of the eight different fields. When predicting recurvature or non-recurvature, the gradients parallel and normal to the proposed track were measured. This orientation was thought to be most sensitive to pressure gradients parallel to the track which would correspond to steering flow normal to the track. When predicting corrections to the analog forecast positions, the gradients were measured North/South and East/West about the point. The distance over which the gradients were measured was six degrees of latitude or three degrees on either side of the respective point. Each gradient measured was a potential predictor.

In the recurvature / non-recurvature problem, the predictand was the square of the distance from the verifying position to the (TYFOON) straight forecast, minus the square

of the distance from the verifying position to the (TYFOON) recurve forecast. In the correction problem, predictands were North/South and East/West distances from the (TYFOON) straight and recurve forecasts to the verifying positions.

The 234 predictors were screened in two steps. The first step ranked the top 50 predictors by size of their coefficient's of correlation with the predictand. The second step selected 12 predictors from this group by the "ridge trace" technique which will be discussed in a later section. The choice of 12 predictors was purely arbitrary.

III. DISCUSSION OF FORECAST TOOLS

A. MODEL OUTPUT STATISTICS

Model Output Statistics is an objective technique which determines the statistical relationship between a predictand and variables forecast by a numerical model. In general application, this statistical relationship is applied to the output of a numerical model, for some model forecast time, to get an estimate of the predictand at that same time.

In this investigation the FNWC primitive equation model supplied the numerical output as was described in the data section. The statistical relationships were determined by a "ridge regression" technique vice ordinary least squares or stepwise regression, and the predictands were either recurvature / non-recurvature or corrections made to a first guess represented by an analog mean position.

B. RIDGE REGRESSION

Ridge regression is a type of biased estimator for data analysis and model building. The name "ridge" is in no way related to the meteorological usage of the term "ridge". Ridge regression is a useful technique for dealing with highly correlated (non-orthogonal) predictor variables because it can develop a set of stable coefficients when more classical methods cannot. Since the predictors used in

this research were highly correlated, ridge regression was used and the results tested against the classical least squares method. The least squares method is inferior for non-orthogonal problems. The large variance inflation of the estimated coefficients, caused by highly correlated predictors, results in highly unstable coefficients. Of course, the presence of gross errors, missing values, and other problems can create nonsense results regardless of the regression techniques, but ridge regression handles these problems better since it utilizes a little bit of several highly correlated variables rather than using some variables and excluding the remaining ones.

The "name of the game" is still coefficient mean square error reduction, but ridge regression does it a little differently than ordinary least squares. Mean square error (MSE) = variance + $(\text{bias})^2$. Two key properties of the least squares estimator are that it is unbiased (bias = 0), and that for orthogonal problems the variance is a minimum. For non-orthogonal problems, however, the variance becomes large and so does the MSE. The ridge regression estimator allows a little bias in exchange for a much smaller variance. Ridge regression then seeks an optimum bias which will reduce the coefficient MSE to a minimum.

Recall from the standard model for multiple linear regression ($Y = XB + e$) that the least squares estimator of (B) is

$$B'' = (X'X)^{-1} X'Y$$

where, (Y) is the vector of observations on the dependent variable, (X) is the matrix of observations on the independent predictor variables, X' is the transpose of X, ($X'X$) is the correlation matrix, (e) is the vector of experimental errors, and (B'') is the vector of population values of the parameter.

The ridge regression estimator (B"*) , as described by Hoerl and Kennard (1970), is

$$B''* = (X'X + kI)^{-1} X'Y$$

where k is a positive constant usually in the range from zero to one. Note that when k=0, B" and B"* are equal. With respect to MSE, variance is a decreasing function of k, and bias is an increasing function of k. In practice, k is added to the diagonal of the correlation matrix, each element of which is identically 1.0, and the matrix is restored to correlation form by dividing through by (1+k). This reduces the size of all the correlation coefficients and thus reduces the apparent non-orthogonality which may improve the numerical analysis. For each value of (k) assigned, a separate inversion of the matrix (X'X + kI) is calculated and a plot of (k) versus each resulting coefficient is made. The result of plotting all the combinations is called the "ridge trace" . (see Figure 2.) The ridge trace is a diagnostic tool which portrays the effects of the non-orthogonality on the system of coefficients, and allows selecion of an optimum bias (k) where the system becomes stable and the MSE of the coefficients may be smaller than that from least squares regression. The ridge trace can also be used to screen predictors by eliminating those with the very small coefficients; however, new computations for another ridge trace must be made for the remaining predictors since the high correlations will have been altered.

The length of the vector B"*, the square root of the sum of squares of its elements, is a maximum for k=0 (ordinary least squares). As (k) increases, the length of B"* decreases. This is important with noisy data where there is some noise associated with each predictor. Since the coefficients tend to be smaller, less noise is included in each term of the predicted value; and since the coefficients tend to be more uniform in magnitude, random noise in the

several terms tends to cancel out.

IV. GENERAL DISCUSSION OF THEORY

A. PREDICTION OF RECURVATURE

To improve upon the analog forecasts it was necessary to first predict which of the two analog schemes (TYFOON RECURVE or TYFOON STRAIGHT) to use as a first guess forecast, that is to predict recurvature or non-recurvature.

The concepts of straight and recurving tropical cyclone tracks are not well defined. For instance, a recurving storm and a straight storm may have identical tracks for several days when South of the subtropical ridge under the influence of the Easterlies. For the purpose of this thesis we classified a storm as recurving if its track turned out, after the fact, to have been better described by the recurving analog track forecast, otherwise it was labeled straight. With this definition of a straight/recurve track it was necessary to make a straight/recurve forecast at each point along the track, and it was possible for a storm to change back and forth between classes, at least while South of the subtropical ridge. Although such forecasts are clearly not independent of each other, they were treated as such. This treatment is tantamount to a statistical assumption which later proved to be a source of trouble.

B. CORRECTICN TO ANALOG FORECASTS

The predictors available for forecasting position corrections were the North/South and East/West gradients at all of the 14 points of figure 1. What we were looking for were predictors that would indicate the displacement of a storm in time from the first guess position which represented a forecast by either a straight or recurving analog scheme. For example, if a basic recurvature path were forecast, we would expect abnormal North/South gradients along the analog track to correspond to abnormal East/West displacements of the cyclone from the analog track.

V. RESULTS

A. FORECAST SCHEMES

Four different forecast schemes were tested and compared to the JTWC official forecasts for a homogenous set of forecast cases.

1. First Guess

After the recurvature forecast was made objectively, the straight or recurvature analog forecast position was used as the forecast.

2. Ridge Regression

After the recurvature forecast was made objectively, the "best" ridge equations were used to correct the analog forecast position. "Best" was determined on dependent data.

3. Least Squares

The same as (2) except that ordinary least squares replaced ridge regression as the method of determining predictive equations.

4. Ridge/First Guess Mix

Essentially the same as (2), except that when straight was forecast, no correction was applied to the straight analog forecast. This recognized that straight storms are South of the subtropical ridge near the boundary of the FNWC primitive equation model in an area where the fields are suspect.

B. FORECAST ERRORS

Recall that in each of the forecast schemes above, the first step was a prediction of straight/recurvature. Our performance in this area was so poor that our forecast results were largely meaningless except for some specialized purposes. We were in the wrong straight/recurvature classification at least half the time, and were usually applying our corrections outside the area for which they were designed. Table 1. compares the relative errors of the various forecast schemes. The better performance of the First Guess scheme over the other three schemes indicates that no correction is superior to a doubtful correction. The Ridge Regression scheme shows some slight though not significant improvement over the Least Squares scheme. The comparison cf scheme (4) to scheme (2) should lend some support to the value of the FNWC fields, since scheme (4) forecasts only where those fields are thought to be most representative at the higher latitudes of the recurving storm.

The forecast improvement (ridge over least squares) was significant when the correct straight / recurvature classification was specified rather than forecast. (see

Table 2.) The relative standings of the various schemes did not change, but more significantly we see that the First Guess scheme (no correction) was still superior to the others.

C. INVESTIGATION OF RESULTS

The prediction of straight / recurvature was very accurate (approximately 90 percent) for the dependent sample. This dropped down to about 45 percent in the independent sample. This suggested any of several classical statistical blunders. Our procedures were investigated for signs of bias or systematic selection of cases or other statistical nonsense.

A comparison of correlation coefficients of dependent and independent data samples was considered elementary to an examination of the data stratification. We wanted to determine whether two correlation coefficients, associated with the same predictor-predictand pairing in both the dependent and independent samples, differed at a .90 confidence level. This was done by using a test statistic derived from Fisher's (z) transformation, which is approximately normally distributed. The correlation coefficients were plotted, dependent against independent. (see Figures 3, 4, and 5) The upper and lower lines (solid) define the area wherein the two correlation coefficients are not significantly different at a .90 level. Figures 3, 4, and 5 show that as the number of forecast cases decreased, the reliability of predictors common to the independent and dependent samples decreased. The Fisher's statistic uses a variance inversely related to the number of cases. Since our correlations frequently differed in excess of that expected, one had to suspect the statistical procedures or

assumptions. After checking the computational procedures, the only assumption of any consequence was that we had "N" independent forecast cases.

When you consider that the average life span of a tropical cyclone may be 3-5 days, then time adjacent measurements of pressure gradients (predictors) at 12 hour intervals during this life span are obviously not independent. In an attempt to test what our effective "N" size was, we speculated that we had one independent case for each tropical cyclone in the independent sample. This must apply to the dependent sample as well, but since the dependent sample was nearly four times as populous as the independent sample, we assumed that the dependent correlation coefficients were accurate. The .90 percent confidence intervals were again computed with the assumed effective "N". (see Figures 3, 4, and 5) The number of points within the .90 confidence interval (dashed lines) increased to reasonable expectations. If the assumption that the dependent coefficients are accurate was true, then the poor forecasting would be solely attributable to bad luck in selection of the independent sample, and would not reflect expected results given a representative group of forecast cases.

The physical "reasonableness" of the predictors used to predict straight / recurvature was examined. Roughly one half appeared to be reasonably related to the predictand, and the remaining appeared to be unrelated from a physics viewpoint. This suggested that physical reasonableness should have been more of a criterion for selecting predictors during the ridge trace analysis vice simply choosing an arbitrary number.

VI. CONCLUSIONS

The objective of determining the usefulness of the outlined approach for predicting recurvature or non-recurvature was inconclusive. Apparent is the requirement for a data set many times as large as the two year sample used here. This suggests a wait of several years or a simulation problem to "manufacture" cases.

The objective of proving the value of ridge regression met with some success. In nearly every confrontation, the "ridge" equations were superior to ordinary least squares. The superiority was striking in only a few instances, however, and even this is clouded since even the best equations could not sustain their promised variance reduction through the test of independent data.

Probably the most valuable conclusion here is that the most fruitful area for application of model output statistics to the tropical cyclone problem is in the basic problem of recurvature / non-recurvature. The results of the attempt to correct a good first guess by the use of synoptic gradients from the FNWC model, though not compelling, are strongly suggestive that such improvement will be minor if any.

TABLE I

Mean forecast errors (NM) when predicting recurvature/non-recurvature.

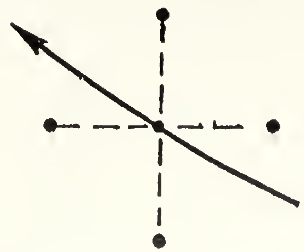
Forecast Period	Official J.T.W.C.	1 First Guess	2 Ridge Regression	3 Least Squares	4 Ridge/First Guess Mix	No. Forecast Cases
24-hr	116	133	151	160	137	125
48-hr	248	253	297	297	271	92
72-hr	401	396	483	530	439	61

TABLE II

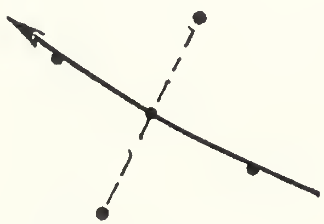
Mean forecast errors (NM) when given recurvature/non-recurvature.

Forecast Period	Official J.T.W.C.	1 First Guess	2 Ridge Regression	3 Least Squares	*	No. Forecast Cases
24-hr	116	110	116	127		125
48-hr	248	182	197	205		92
72-hr	401	237	284	319		61

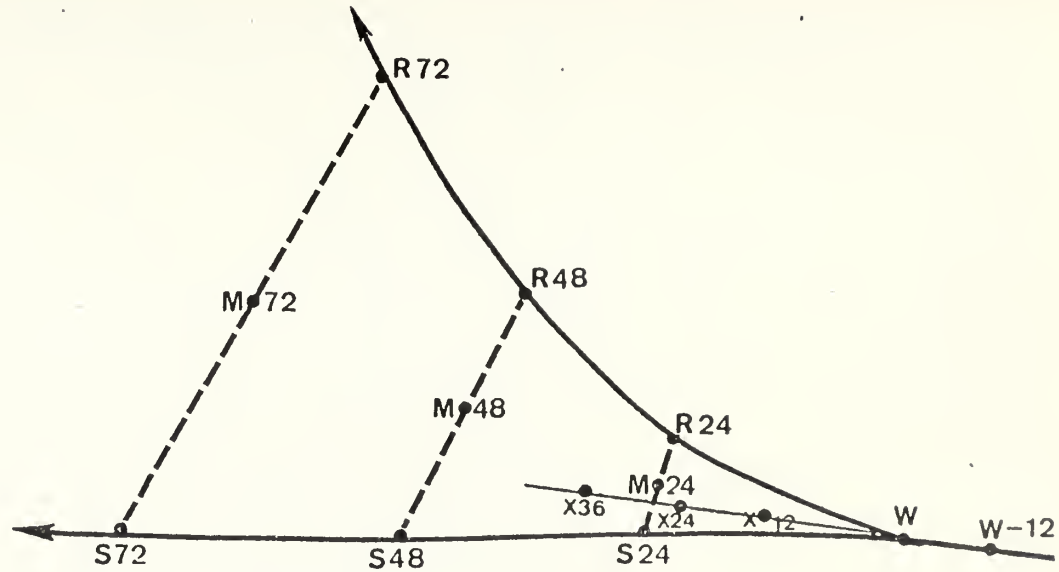
* Ridge/First Guess Mix not calculated.



Predicting corrections



Predicting S/R



Legend:

R - TYFOON RECURVE forecast positions
S - TYFOON STRAIGHT forecast positions
M - midpoint between R and S
X - extrapolated positions
W - J.T.W.C. warning positions

Figure 1 - Schematic of predictor measurement points

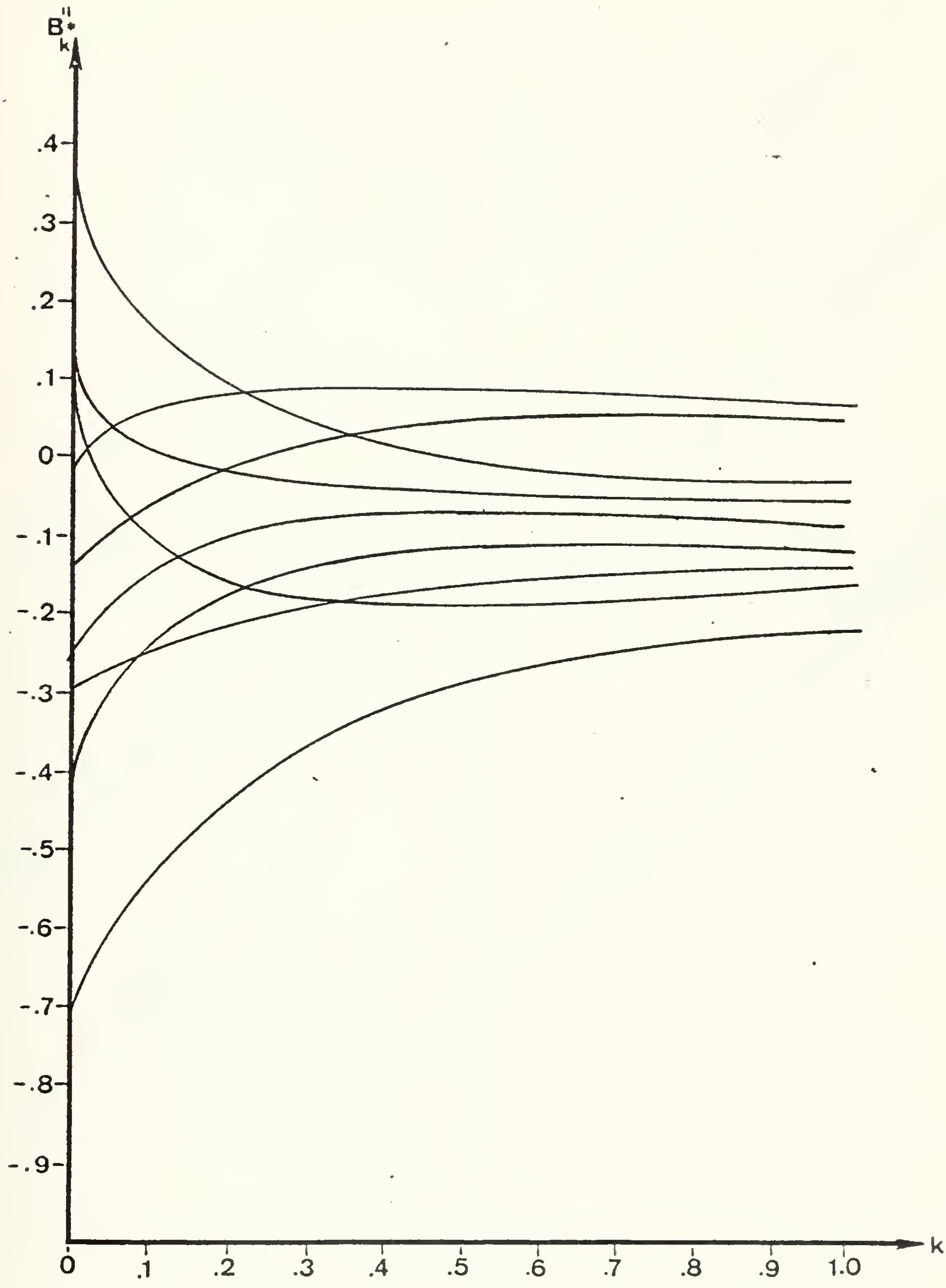


Figure 2 - Example of a ridge trace.

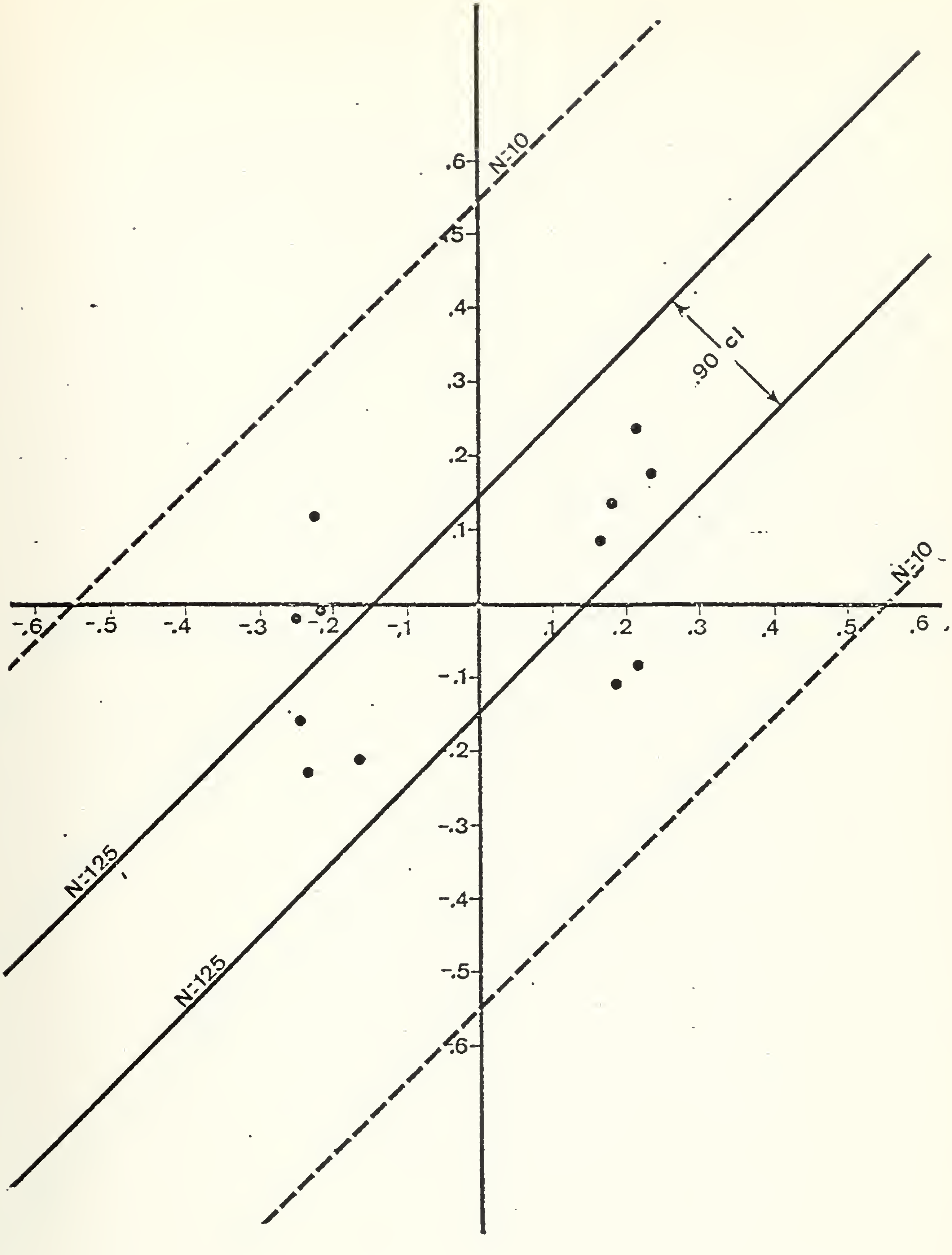


Figure 3 - 24 hour straight/recurve prediction, dependent vs. independent correlation coefficients.

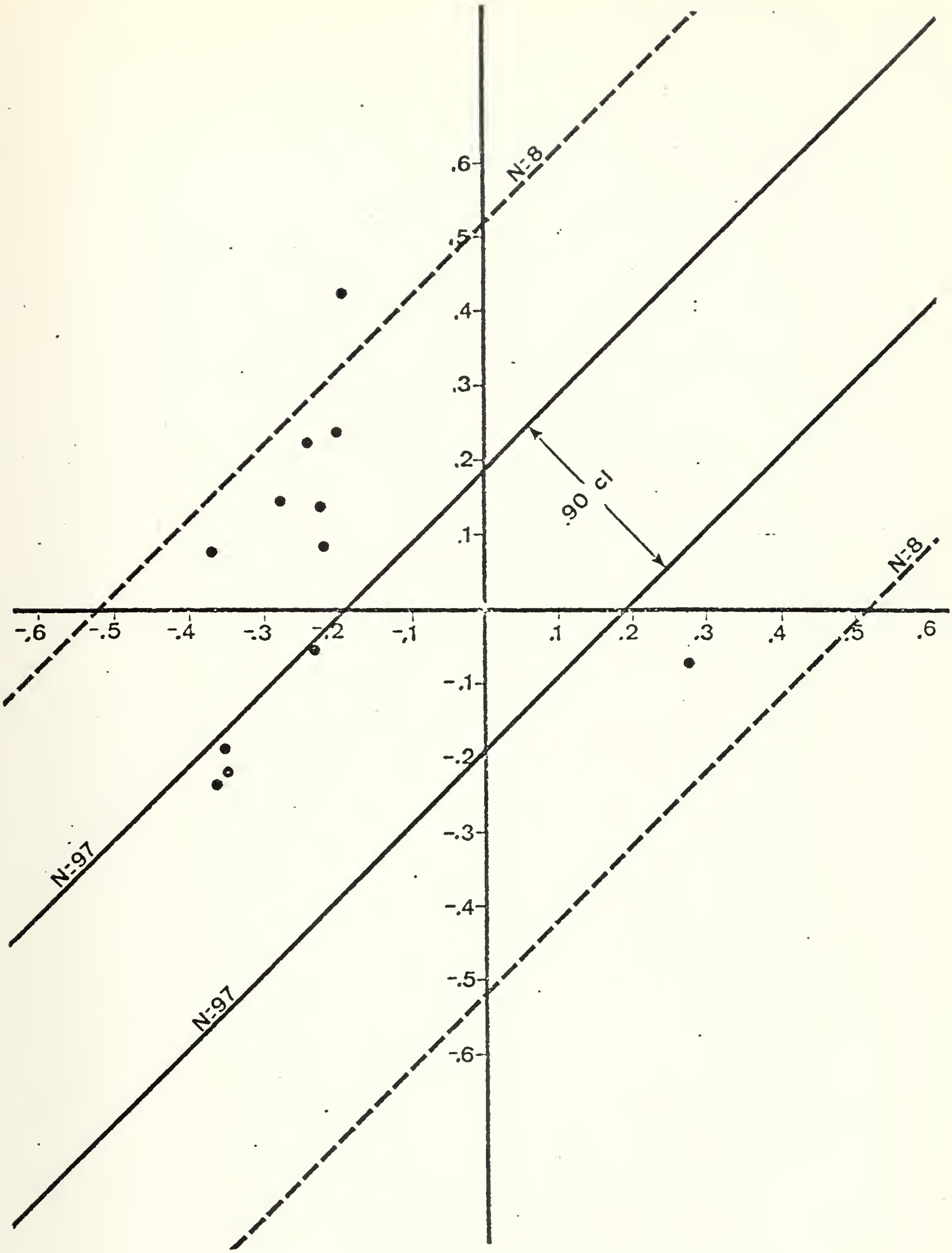


Figure 4 - 48 hour straight/recurve prediction, dependent vs. independent correlation coefficients.

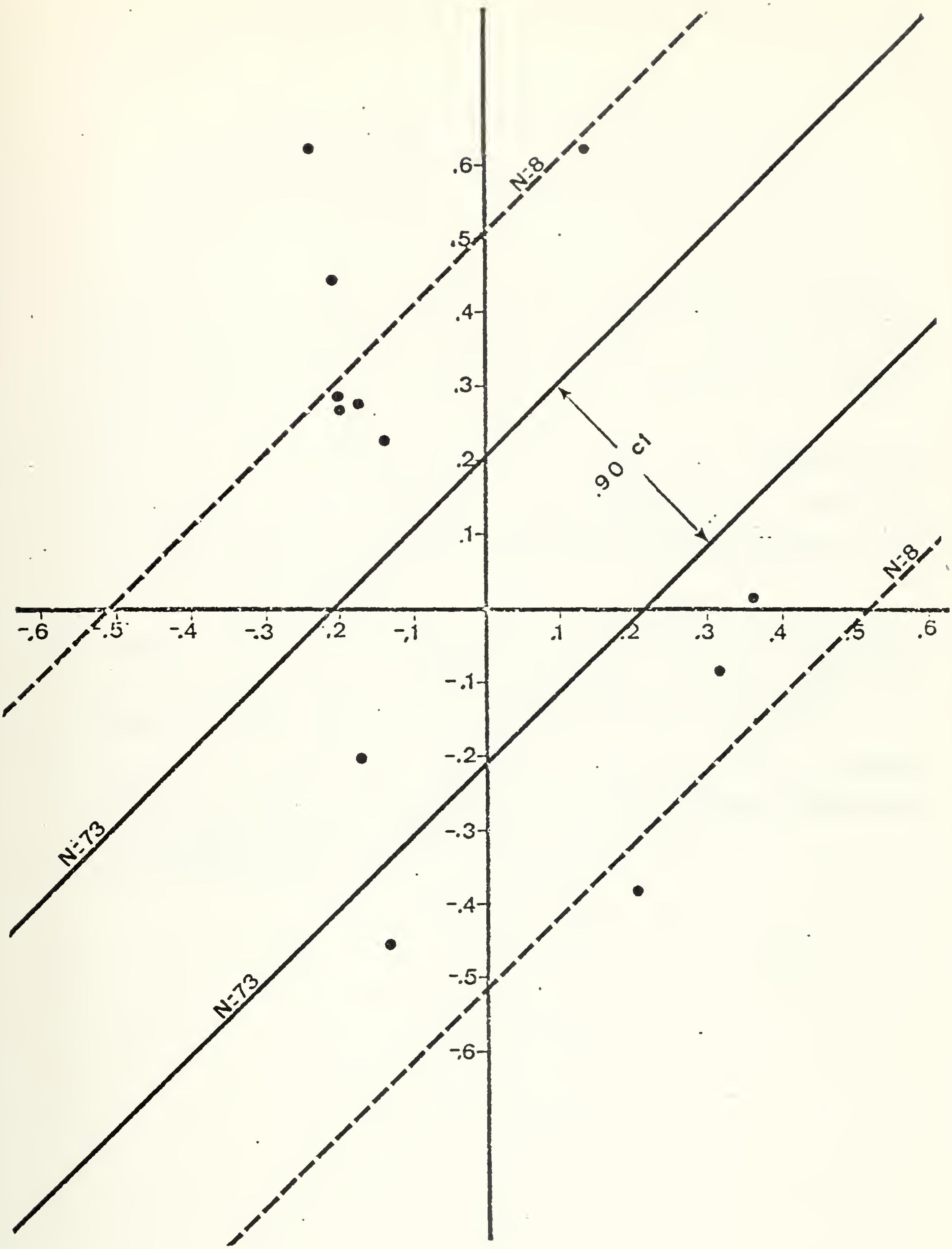


Figure 5. - 72 hour straight/recurve prediction, dependent vs. independent correlation coefficients.

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